

## Research Article

# Orthogonal Experimental Study on Multifactor Conditions for Gas Desorption in Coal

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Received 11 October 2018; Revised 18 December 2018; Accepted 2 January 2019; Published 19 March 2019

Academic Editor: Fan Gu

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The isothermal adsorption experiment of coal is an important method to study the mechanism of coal gas desorption. The orthogonal experiment is used to compare the gas desorption mechanism of coal under multifactor conditions, such as the particle size, temperature, pressure, moisture content, and molding pressure. The sensitivity of five factors was used to conduct regression analysis. The sensitivity and influence degree of five factors on the coal gas desorption capacity were analyzed. The results showed the following: (1) the effect of the coal sample particle size, temperature, pressure, moisture content, and molding pressure of coal on the sensitivity of desorption capacity is shown as C (pressure) > B (temperature) > A (particle size) > D (moisture content) > E (molding pressure); (2) the regression analysis of various factors for gas adsorption indicates that the degree of correlation of the multivariate quadratic regression equation is higher compared to that of the multivariate one-time regression equation; and (3) the coal sample particle size, temperature, pressure, moisture content, and type of gas desorption can well represent the gas desorption capacity of a coal sample under various conditions. The smaller the particle size of the coal sample, the higher the ambient temperature, the higher the gas pressure, the lower the moisture content of the coal sample, and the greater the gas desorption per unit mass in 30 min after coal sample gas adsorption equilibrium. The orthogonal test results have important theoretical significance for guiding gas adsorption and desorption tests of coal. For coal and gas outburst prediction, the coal seam gas flow mechanism, coal gas content prediction, and calculation of the mining coal gas emission have important practical significance for gas explosion accident prevention.

## 1. Introduction

Coal is the world's most abundant, widely distributed, most accessible, and cheapest source of energy. Due to the rapid development of the global economy, the demand and consumption of various energy sources in the world have risen sharply, and the exploitation of coal resources has also increased daily [1]. Coalbed methane is a companion mineral resource produced during the formation of coal with methane as the main component. Coalbed methane is commonly known as gas. It is a new and unconventional clean energy source that has attracted increased attention in the past 20 years, but coalbed methane is flammable and has

explosive characteristics. Coalbed methane often causes coal mine gas explosion accidents, thereby endangering the safety of employees and property of coal mining enterprises [2].

The gas desorption and diffusion process of coal is closely related to the prediction of coal and gas outburst and is mainly applied in the determination of the gas content in coal seams and gas desorption index of drill cuttings [3, 4]. Regarding the mechanism of gas desorption and diffusion of coal, most scholars believe that the dynamic process of gas diffusion of coal at atmospheric pressure follows Fick's law of diffusion with the concentration gradient as the driving force, and the simplified model of homogeneous gas particle diffusion [5–8] is as follows:

$$\frac{Q_t}{Q_\infty} = \sqrt{1 - e^{-Kt}}, \quad (1)$$

$$B = \frac{\pi^2 D}{a^2},$$

where  $Q_t$  is the gas volume of desorption and diffusion per unit mass coal sample at time  $t$  ( $\text{m}^3/\text{t}$ ),  $Q_\infty$  is the gas volume of desorption and diffusion per unit mass coal sample when  $t \rightarrow \infty$  ( $\text{m}^3/\text{t}$ ),  $K$  is a constant (0.96),  $D$  is the diffusion coefficient of coal dust ( $\text{cm}^2/\text{s}$ ),  $a$  is the radius of the coal particles (cm), and  $t$  is the desorption time (s).

From this model, it can be seen that the factors related to the coal adsorption gas volume and diffusion coefficient affect the gas desorption and diffusion of coal. Therefore, domestic and foreign scholars have carried out a large number of experimental studies on the desorption and diffusion process of gas-containing coal and have focused on the characteristics of the test and the characteristics of the coal, such as the adsorption equilibrium pressure [9, 10], the degree of coal metamorphism [10], the composition of coal [11], and the influence of temperature [4, 12] on the mechanism of gas desorption.

The isothermal adsorption experiment of coal is an important means for the experimental study of coal gas desorption. At present, many scholars have studied individual influence factors related to isothermal adsorption experiments. Zhang et al. [13] systematically studied the effects of particle size, pressure, experimental temperature, and equilibrium time on the adsorption performance of coal with different metamorphic degrees and analyzed the influence of various factors on the results of isothermal adsorption experiments. Yue et al. [14] experimentally studied the effect of different temperature conditions. The gas desorption mechanism of coal was obtained, and the gas desorption rate of coal was much slower at lower than normal temperatures. Chen et al. [15] studied the isothermal adsorption and desorption characteristics of coal samples of the same coal quality but with different particle sizes. Geng et al. [16] determined the desorption under normal temperature conditions and the effect of a temperature rise on strengthening gas desorption during tests on gas-containing lump coal with different water contents under natural and high-pressure water injection conditions. Zhang et al. [17] proposed an isothermal adsorption experimental data processing method by comparing the isothermal adsorption curves of pure methane gas before and after the adsorption-phase volume correction. Based on Fick's second law, Yue et al. [18] discovered that the adsorption equilibrium pressure is approximately 1.4 MPa under experimental temperature conditions of 35°C–65°C, when they studied the adsorption and diffusion behaviors of methane ( $\text{CH}_4$ ) and carbon dioxide ( $\text{CO}_2$ ) in coal samples with different ranks.

Clarkson et al. [19] calculated binary gas adsorption/desorption isotherms. Joubert et al. [20] conducted sorption experiments of methane in moist coal and found that the adsorption capacity of methane decreased with increasing moisture content until the critical moisture content was reached. When the moisture content was greater than the

critical moisture content, excess water had no effect on the gas adsorption capacity. The results of Yin et al. [21] showed that the moisture content had a greater impact on the gas permeability of gas-bearing coal seams. Wei et al. [22] considered that water had a significant effect on the permeability of gas-containing coal at a constant temperature. Studies by Pan et al. [23] have shown that the matrix moisture content has a significant effect on the gas adsorption capacity and plays a key role in desorption and migration.

From the results of these studies, it is evident there are few studies on the effect of specific factors on the coal desorption mechanism of coal under normal pressure conditions, such as the particle size, temperature, pressure, moisture content, and coal sample forming pressure, or there is a lack of systematic test data support. In this paper, the effects of the coal sample particle size, temperature, pressure, moisture content, and coal sample forming pressure on the coal gas desorption mechanism are studied by orthogonal testing. It is necessary to ascertain the priority of each influence factor on the gas desorption of coal to meet the goal of the study. Studying the desorption mechanism of gas-containing coal has important practical significance for coal and gas outburst prediction, coal seam gas flow mechanism determination, coal gas content prediction, coal gas emission calculation, and gas explosion accident prevention.

## 2. Experimental Study

**2.1. Experimental Equipment.** To study the influence of multiple factors on the gas desorption and adsorption mechanism of coal under different temperature and environmental conditions, particularly under low-temperature conditions, a high-low temperature coal gas desorption and adsorption experimental platform was built. The experimental platform was mainly composed of five parts: a high and low temperature-frequency conversion control system, adsorption balance unit, vacuum degassing unit, desorption measurement control unit, and real-time data acquisition system. The structure of the experimental platform is shown in Figure 1.

The components of the experimental platform are as follows:

- (1) The temperature variation range of the high and low temperature-variable frequency control system is  $-50^\circ\text{C}$  to  $50^\circ\text{C}$ , while the temperature deviation is  $\leq \pm 1^\circ\text{C}$  and the temperature fluctuation is  $\pm 0.5^\circ\text{C}$ .
- (2) The adsorption balance unit is composed of a precision pressure sensor, cylinders with gas at a pressure of 15 MPa and with a purity of 99.9%, a reference tank, a sample tank, and various control valves. The multifunction coal sample tank can measure the gas desorption of coal in real time and the temperature change during the adsorption.
- (3) The vacuum degassing unit is composed of a resistance vacuum gauge ( $1-1 \times 10^5$  Pa), a vacuum pump (extreme vacuum degree  $6.8 \times 10^{-2}$  Pa), a vacuum tube, and a three-way valve.

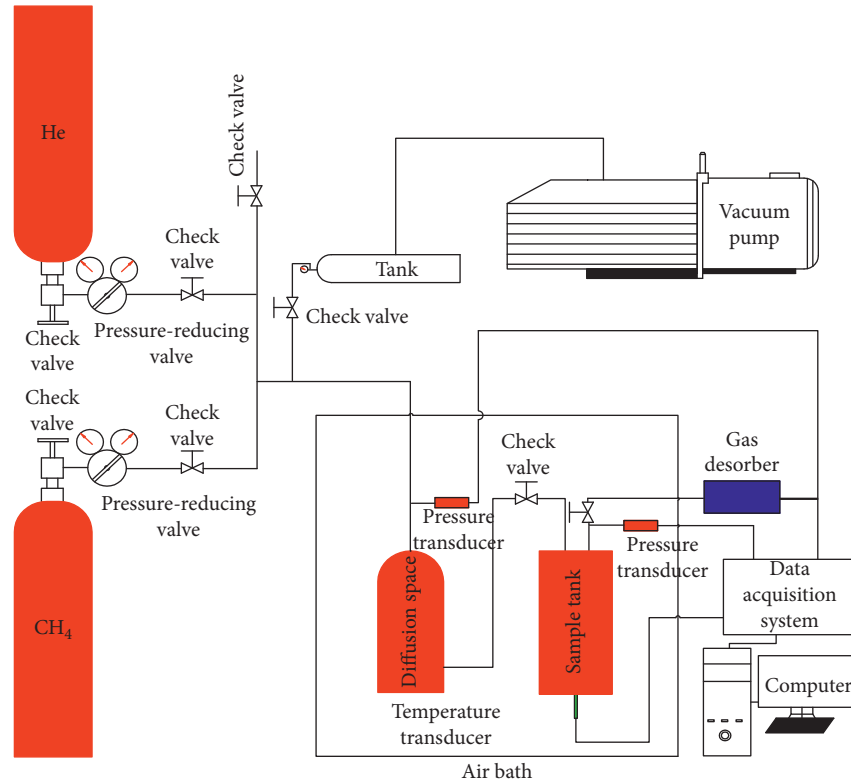


FIGURE 1: Schematic diagram of the experimental platform for the high-low temperature coal gas desorption and adsorption experiments.

- (4) The desorption measurement control unit is composed of a pressure-regulating valve and a gas desorption-measuring instrument. The pressure-regulating range of the pressure-regulating valve is 0–16 MPa, and the pressure-regulating scale is 0.005 MPa/unit; the gas desorption-measuring instrument is composed of a descaling-measuring cylinder with a scale. The inner diameter of the measuring tube is 50 mm, the height is 500 mm, the volume is 1000 ml, and the minimum precision is 2 ml.
- (5) The real-time data acquisition system transmits the test data of the experiment to the data acquisition system through temperature and pressure sensors, and the data acquisition system is connected to a computer to realize the real-time collection of the test data.

**2.2. Sampling and Preparation.** The experimental coal samples consisted of coking coal taken from the No. 4 coal seam of the Nantong Coal Mine in Chongqing. After the fixed sampling of the coal seam, the coal samples were processed and proximate analyzed according to the proximate analysis method of coal (GB/T212-2008) [24]. The proximate analysis results are shown in Table 1. Because the experiments were aimed at studying the coal gas desorption and adsorption mechanism of coal briquettes at different molding pressures, preparation of the briquette samples was carried out according to the experimental design constraints of moisture content and molding pressure.

TABLE 1: Proximate analysis of the coal samples.

$M_{ad}$ (%)	$A_{ad}$ (%)	$V_{daf}$ (%)	$C_{daf}$ (%)	$S_{t,d}$ (%)	$Q_{gr,ad}$ (J/g)
0.98	15.95	18.12	64.95	2.58	30.32

Note:  $M_{ad}$  is the moisture content on a dry air basis (%);  $A_{ad}$  is the ash content on a dry air basis (%);  $V_{daf}$  is the volatile matter content on a dry-ash-free basis (%);  $C_{daf}$  is the fixed carbon content on a dry-ash-free (daf) basis (%);  $S_{t,d}$  is the total sulfur content (%);  $Q_{gr,ad}$  is the high calorific value of the sample (J/g).

After the coal samples were dried, they needed to be manually humidified to prepare coal samples with different moisture contents. A schematic diagram of the coal humidification process is shown in Figure 2. The water in the distillation bottle was heated by a heater to distill it. The water was mixed with the coal sample to obtain a water-saturated coal sample, and then the coal sample was dried to different degrees according to the literature [25] or the vacuum degassing method was used to obtain a coal sample with the required moisture content; afterwards, a small amount of the coal sample was selected. Drying and weighing were used to measure the moisture content, and the moisture content of the obtained coal sample was examined.

**2.3. Experimental Design.** An orthogonal experiment [26] is a method of designing and comparing experiments using an orthogonal table and achieving the best experimental results with as few experiments as possible. Because the gas desorption performance of coal is affected by many factors, including the temperature, adsorption pressure, coal

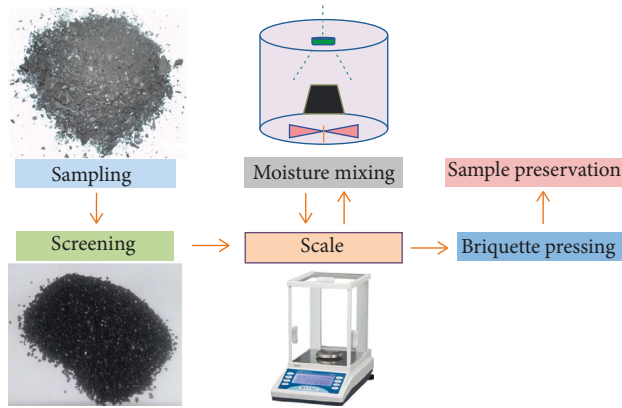


FIGURE 2: Humidification process of the coal samples.

sample size, and moisture content, to explore the influence of multiple factors on the coal gas desorption and adsorption performance, it is often necessary to repeat a large number of experiments. The experimental procedure is cumbersome, and the experimental period is long. Therefore, the orthogonal experimental design method is adopted to conduct the gas adsorption/desorption experiment of the coal samples, and the gas desorption and adsorption mechanism of the coal samples under multi-factor conditions is analyzed.

The five factors influencing the gas adsorption/desorption performance of the coal samples analyzed in this paper included the coal sample particle size, temperature, pressure, moisture content, and coal sample molding pressure. Each factor had five experimental levels, so orthogonal table L25 ( $5^6$ ) was selected. To fulfill the five levels of design requirements and the six factors of the orthogonal table, it was necessary to include another factor that was not related to the experiment, which was based on five experimental setting factors. The factors and levels of the orthogonal experiment are shown in Table 2.

The experimental scheme designed according to the L25 ( $5^6$ ) orthogonal table is shown in Table 3.

**2.4. Experimental Procedure.** Before loading the coal sample into the coal sample tank, first, the airtightness test of the experimental device was carried out to ensure that the connection between the tank body, the pipeline, and the valve of the entire experimental platform was tight and airtightness had been achieved. The subsequent experimental steps were as follows:

- (1) The experimental platform was evacuated. First, the gas remaining in the experimental device when the airtightness test was conducted was exhausted, and thereafter, the exhaust valve was closed; then, the vacuum valve to the vacuum pump was opened. The vacuuming time was not less than 8 h and lasted until the measured internal pressure of the experimental device was 0.01 MPa or less.
- (2) The free space of the experimental device was measured. At a certain pressure (approximately

0.4 MPa), helium (He) gas was charged into the reference tank, and voltage regulation was performed for 10 min. After the pressure had stabilized, the reference tank was opened to allow He to enter the sample tank; voltage regulation was then conducted for 20 min, and the free space in the sample tank was calculated according to the gas state equation.

- (3) Gas desorption of the coal sample was determined under pressure relief. Under the designed temperature and environment conditions, methane was charged at the design pressure and regulated into the reference tank for 10 min. According to the experimental design, the temperature of the incubator was set and the sample was adsorbed for at least 8 h. Then, the gas desorption operation was performed, and the desorption readings were recorded every 1 min until a volume of less than 5 ml was observed within 10 min. The volume measurements recorded at ambient temperature and pressure were then converted to standard volumes using the desorption pressure of the desorbed gas according to the ideal gas law [14]:

$$PV = nZRT, \quad (2)$$

where  $P$  is the absolute adsorption equilibrium gas pressure (Pa),  $V$  is the desorbed gas volume ( $\text{m}^3$ ),  $n$  is the gas molar weight (mol),  $Z$  is the compressibility coefficient (dimensionless),  $R$  is the universal gas constant ( $\text{J}/(\text{mol}\cdot\text{K})$ ), and  $T$  is the thermodynamic temperature (K).

Following the experimental procedure, the determination steps of the desorbed gas volume of the coal sample were repeated, and all experiments were completed.

### 3. Results: Sensitivity and Regression Analysis

**3.1. Sensitivity Analysis.** According to the orthogonal scheme, the gas desorption and adsorption experiments of 25 coal samples under different conditions were carried out. The cumulative desorption of gas in 30 min after reaching gas adsorption equilibrium was measured for 25 sets of experimental coal samples. Because the mass of the coal sample in each set of experiments was constant at 320 g, the measured gas desorption volume data were processed to obtain a gas desorption volume per unit mass within 30 min. As an index to investigate the gas desorption capacity of coal, a sensitivity analysis of the effect of various factors on the gas desorption capacity of the coal samples was carried out. The results of the sensitivity analysis of the gas desorption per unit mass in 30 min are shown in Table 4.

According to the sensitivity analysis results in Table 4,  $R_A = 3.91$ ,  $R_B = 4.58$ ,  $R_C = 20.19$ ,  $R_D = 3.83$ , and  $R_E = 1.39$ . Sorting the range of results of the five factors results in  $R_C > R_B > R_A > R_D > R_E$ , and thus, the sensitivity of the gas desorption per unit mass in 30 min to the five factors is C (pressure) > B (temperature) > A (particle size) > D (moisture content) > E (molding pressure).

TABLE 2: Factors and levels of orthogonal experiment L25 ( $5^6$ ).

Level	A: particle size (mm)	B: temperature ( $^{\circ}$ C)	C: pressure (MPa)	D: moisture content (%)	E: molding pressure (kN)	F: empty form
1	2.0–5.0	30	5.0	10	200	1
2	1.0–2.0	10	4.0	8	170	2
3	0.5–1.0	0	3.0	6	140	3
4	0.25–0.5	–10	2.0	4	110	4
5	0.2–0.25	–30	1.0	2	80	5

TABLE 3: Orthogonal experimental design.

Level	A: particle size (mm)	B: temperature ( $^{\circ}$ C)	C: pressure (MPa)	D: moisture content (%)	E: molding pressure (kN)	F: empty form
1	2.0–5.0	30	5.0	10	200	1
2	2.0–5.0	10	4.0	8	170	2
3	2.0–5.0	0	3.0	6	140	3
4	2.0–5.0	–10	2.0	4	110	4
5	2.0–5.0	–30	1.0	2	80	5
6	1.0–2.0	30	4.0	6	110	5
7	1.0–2.0	10	3.0	4	80	1
8	1.0–2.0	0	2.0	2	200	2
9	1.0–2.0	–10	1.0	10	170	3
10	1.0–2.0	–30	5.0	8	140	4
11	0.5–1.0	30	3.0	2	170	4
12	0.5–1.0	10	2.0	10	140	5
13	0.5–1.0	0	1.0	8	110	1
14	0.5–1.0	–10	5.0	6	80	2
15	0.5–1.0	–30	4.0	4	200	3
16	0.25–0.5	30	2.0	8	80	3
17	0.25–0.5	10	1.0	6	200	4
18	0.25–0.5	0	5.0	4	170	5
19	0.25–0.5	–10	4.0	2	140	1
20	0.25–0.5	–30	3.0	10	110	2
21	0.2–0.25	30	1.0	4	140	2
22	0.2–0.25	10	5.0	2	110	3
23	0.2–0.25	0	4.0	10	80	4
24	0.2–0.25	–10	3.0	8	200	5
25	0.2–0.25	–30	2.0	6	170	1

TABLE 4: Sensitivity analysis results of the gas desorption amount per unit mass in 30 min.

Level	A: particle size (mm)	B: temperature ( $^{\circ}$ C)	C: pressure (MPa)	D: moisture content (%)	E: molding pressure (kN)
$k_1$	16.65	16.25	27.35	17.48	18.82
$k_2$	18.18	16.69	23.90	17.88	18.94
$k_3$	17.12	19.59	20.04	19.16	18.18
$k_4$	20.56	18.23	13.14	20.46	18.12
$k_5$	19.09	20.83	7.16	16.63	17.54
R	3.91	4.58	20.19	3.83	1.39

Therefore, according to the analysis of the experimental data, the five factors, namely, the coal particle size, temperature, gas pressure, coal sample moisture content, and coal sample molding pressure, had a certain degree of influence on the gas desorption capacity of coal, but the influence of each of the five factors on the gas desorption capacity was different. The gas pressure had the most significant effect on the gas desorption of coal, followed by the gas desorption temperature, the particle size of the coal sample, the moisture content of the coal sample, and the molding pressure of the coal sample.

**3.2. Regression Analysis.** To better analyze the influence of the coal particle size, temperature, gas pressure, coal sample moisture content, and coal sample forming pressure on the gas desorption capacity of coal, the regression results dataset of the coal gas desorption experiment was analyzed. To capture the behavior of the gas desorption per unit mass in 30 min as a function of the particle size, temperature, gas pressure, coal sample moisture content, and coal sample forming pressure, an equation with a high degree of correlation needed to be fitted to the experimental data.

The gas desorption amount per unit mass in 30 min is defined as  $Q$ , and the coal sample particle size, temperature, gas pressure, coal sample moisture content, and coal sample forming pressure are defined as  $x_1, x_2, x_3, x_4$ , and  $x_5$ , respectively.  $Q, x_1, x_2, x_3, x_4$ , and  $x_5$  represent only the numerical values and are dimensionless.

First, a multivariate one-time regression analysis was performed on  $Q$  as a function of  $x_1, x_2, x_3, x_4$ , and  $x_5$ , and the multivariate one-time regression equation is shown as follows:

$$Q = 7.63758 - 0.82363x_1 + 0.02330x_2 + 5.11344x_3 - 0.53516x_4 - 0.00290x_5. \quad (3)$$

The correlation coefficient of the multivariate one-time regression equation was 0.9122, which shows that formula (3) could represent the numerical relationship well between the five variables and the gas desorption per unit mass in 30 min,  $Q$ . However, to obtain a multivariate regression equation with an improved correlation coefficient, accuracy, and credibility,  $Q$ , as a function of  $x_1, x_2, x_3, x_4$ , and  $x_5$ , was subjected to multivariate quadratic regression analysis. The factors included in the regression equation were  $x_1, x_1^2, x_2, x_2^2, x_3, x_3^2, x_4, x_4^2, x_5$ , and  $x_5^2$ , and the multivariate quadratic regression analysis equation is shown as follows:

$$Q = -7.67703 + 0.30120x_1^2 - 1.96530x_1 - 0.00024x_2^2 + 0.02330x_2 - 0.57815x_3^2 + 8.58233x_3 + 0.00095x_4^2 - 0.54658x_4 - 0.00067x_5^2 + 0.18457x_5. \quad (4)$$

At this point, the correlation coefficient of the multivariate quadratic regression equation was 0.9696, which was greater than the correlation coefficient of the multivariate one-time regression equation of 0.9122. Therefore, it was concluded that, in the regression analysis of the gas desorption capacity index  $Q$  of coal and the five influence factors, namely, the particle size, temperature, gas pressure, coal sample moisture content, and coal sample forming pressure, the correlation coefficient of the multivariate quadratic regression equation was greater compared to that of the multivariate one-time regression equation. Figure 3 shows a comparison of the multivariate quadratic regression and the multivariate one-time regression analysis.

It can be seen from Figure 3 that the multivariate quadratic regression was more accurate compared to the multivariate one-time regression analysis and was more in line with the values of the indicator.

## 4. Discussion

**4.1. Effect of the Particle Size on the Desorption Properties of Coal.** To study the influence of the coal particle size on the gas desorption properties of coal, the influence of the other four factors on the desorption properties of coal was excluded. First, the particle size (factor A) was selected as the variable, while the other four factors were considered constant values and substituted into equation (4). Second, the multivariate quadratic regression analysis equation was

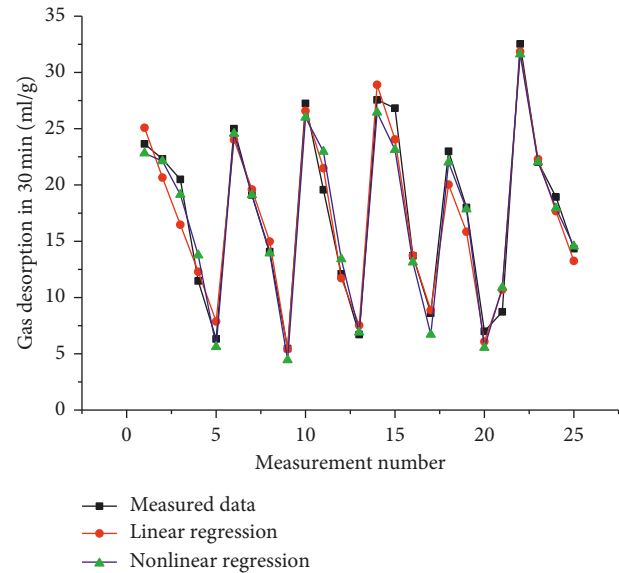


FIGURE 3: Comparison of the multivariate quadratic regression and multivariate one-time regression analysis.

transformed. Then, to obtain  $Q$ , the gas desorption amount per unit mass in 30 min, as a function of the particle size,  $x_1$ , the intermediate level of the experimental design for the remaining four factors was selected:

$$\begin{aligned} x_2 &= 0, \\ x_3 &= 3, \\ x_4 &= 6, \\ x_5 &= 140. \end{aligned} \quad (5)$$

The values of the above four factors were substituted into the multivariate quadratic regression analysis equation to obtain the relation of  $Q$  with respect to the particle diameter  $x_1$ , as shown in formula (6). The curve of the gas desorption amount per unit mass in 30 min as a function of the particle size is shown in Figure 4:

$$Q = 22.33874 + 0.30120x_1^2 - 1.96530x_1. \quad (6)$$

According to Figure 4, as the particle size of the coal sample gradually decreased, the gas desorption per unit mass in 30 min gradually increased after coal sample balancing, and the rate of gas desorption decreased.

Coal is a porous medium that has a very strong adsorption affinity for gas and contains a large number of cracks and pores. The adsorption and desorption of gas in coal is a reversible process, and the adsorbed gas and free gas in coal affect each other as the external environment changes. However, the content of adsorbed gas in coal is different from that of free gas, which constitutes most of the gas content of coal.

Chen et al. [27] showed that the total specific surface area of the micropores in coal is usually 5–10 times greater than the specific surface area of the small holes and mesopores. Therefore, the number of micropores is critical to the size of the specific surface area. As the particle size of coal decreases, the total pore volume and total specific surface area of coal

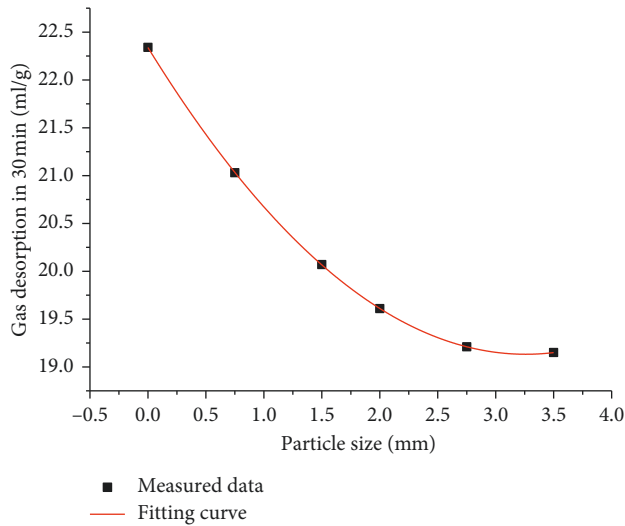


FIGURE 4: Curve of the gas desorption amount per unit mass in 30 min versus the particle size.

gradually increase. The increase in pore volume and specific surface area enhances the adsorption of methane, which causes coal that consists of small-sized particles to contain more gas due to the enhanced gas adsorption capacity. Therefore, the relationship between the desorption capacity of coal and the particle size of coal can explain the overall trend of a negative correlation between the coal sample particle size and desorption capacity of the coal sample as observed in the variation curve resulting from the multivariate quadratic regression analysis.

According to the obtained equation of the particle size and desorption amount, the gas desorption amount per unit mass of the coal sample in 30 min will increase with the gradual decrease in the particle size of the coal sample. However, in the experimental study of the effect of the actual coal sample particle size on gas desorption and adsorption properties of coal, the gas desorption or adsorption amount of coal did not increase with the decrease in coal sample particle size. Instead, there was a particle size limit that constrained the particle size reduction of the coal sample. When the particle size was larger than the particle size limit, the gas adsorption increased with decreasing particle size. However, when the coal sample particle size was smaller than the limit, the effect of reducing the particle size of the coal on the adsorption and desorption of gas was very small. When the particle size of the coal sample was small enough, the particle size of the coal sample continued to decrease, which would increase the degree of fracturing of the coal sample, and the internal structure of the coal particles and the internal space were damaged. At this time, although the reduction in the particle size of the coal sample could increase the external surface area of the coal, the pore surface area inside the coal sample was also destroyed to a certain degree, and the overall contact area between the coal and the gas did not increase substantially. The gas adsorption and desorption in coal did not increase to a great extent, and the change was not notable [28]. Therefore, the equation obtained by regression analysis could reflect the tendency of the gas desorption capacity of

coal to gradually increase with the decrease in coal particle size but did not reflect the coal sample particle size reduction limit. That is, when the coal sample particle size was smaller than the particle size limit value, the gas desorption capacity of the coal sample did not change significantly.

*4.2. Effect of the Temperature on the Desorption Properties of Coal.* To study the influence of the coal temperature on the gas desorption properties, the influence of the other four factors on the desorption properties was excluded. First, the temperature (factor B) was selected as the variable, and the other four factors were defined as constants and substituted into the equation. Second, the multivariate quadratic regression analysis equation was calculated and transformed. After that, the gas desorption amount per unit mass in 30 min,  $Q$ , was obtained as a function of the temperature,  $x_2$ . The intermediate-level values of the experimental design for the remaining four factors were as follows:

$$\begin{aligned} x_1 &= 0.75, \\ x_3 &= 3, \\ x_4 &= 6, \\ x_5 &= 140. \end{aligned} \quad (7)$$

The values of the above four factors were substituted into the multivariate quadratic regression analysis equation to obtain a function of  $Q$  with respect to temperature,  $x_2$ , as shown in equation (8). A graph of the gas desorption amount per unit mass in 30 min as a function of the temperature is shown in Figure 5:

$$Q = 21.03420 - 0.00024x_2^2 + 0.02330x_2. \quad (8)$$

According to Figure 5, as the experimental temperature gradually increased, the amount of gas desorption per unit mass in 30 min gradually increased after equilibrium of the coal sample was reached. Therefore, a high temperature promotes the gas desorption performance of coal, and a low temperature suppresses the gas desorption performance of coal.

As the second most important factor in the sensitivity analysis of the gas desorption performance of coal, the temperature played an important role in the study of the gas desorption mechanism and performance. The coal did not undergo either solely gas desorption or gas adsorption under any of the conditions but rather a superposition of the states of gas desorption and adsorption; coal will be in a state of equilibrium between desorption and adsorption under natural conditions. The gas desorption process of coal is an endothermic process, while the gas adsorption process is an exothermic process. Ma et al. [29] believed that when the ambient temperature of a coal sample rises, the gas desorption equilibrium of the coal sample will move toward gas desorption of coal. At the same time, gas desorption of coal is greater compared to gas adsorption, so the overall gas desorption process of coal is presented. Moreover, the increase in the ambient temperature also causes an increase in the internal energy of the gas adsorbed inside the coal

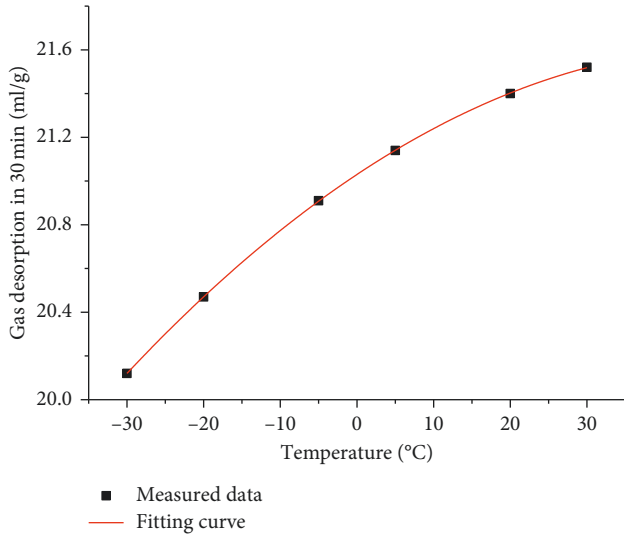


FIGURE 5: Curve of the gas desorption amount per unit mass in 30 min versus the temperature.

matrix, and the random movement of gas molecules is intensified, thereby causing desorption.

Wang et al. [30] found that the gas desorption of coal at a constant temperature of  $-36^{\circ}\text{C}$  was lower compared to the gas desorption at a temperature below  $-36^{\circ}\text{C}$ , while the room temperature gas desorption was lower than the gas desorption at normal temperatures. The gap between the gas desorption amounts under the three experimental conditions gradually increased with the passage of time, indicating that the inhibiting effect of low-temperature conditions on coal gas desorption was very significant. Wang et al. [31] found that the lower the temperature, the stronger the inhibition of coal gas desorption. The lower the temperature, the lower the gas desorption of coal and the more significant the inhibition of gas desorption.

**4.3. Effect of the Pressure on the Desorption Characteristics of Coal.** To study the influence of the adsorption pressure on the gas desorption characteristics of coal, the influence of the other four factors on the desorption characteristics of coal was excluded. First, the pressure (factor C) was selected as the variable, and the other four factors were defined as constant values and substituted into the equation. Second, the multivariate quadratic regression analysis equation was calculated to obtain the functional relationship between the gas desorption amount per unit mass in 30 min,  $Q$ , and the pressure,  $x_3$ . The intermediate-level values of the experimental design for the remaining four factors were as follows:

$$\begin{aligned} x_1 &= 0.75, \\ x_2 &= 0, \\ x_4 &= 6, \\ x_5 &= 140. \end{aligned} \quad (9)$$

The values of the above four factors were substituted into the multivariate quadratic regression analysis equation, and

the functional relation of  $Q$  with respect to the pressure  $x_3$  was obtained, as shown in formula (10). A graph of the gas desorption amount per unit mass in 30 min with the change in pressure is shown in Figure 6:

$$Q = 0.49055 - 0.57815x_3^2 + 8.58233x_3. \quad (10)$$

According to Figure 6, as the experimental gas pressure gradually increased, the amount of gas desorption per unit mass in 30 min increased gradually after coal sample balancing. However, the increase rate gradually decreased and remained basically unchanged after 7 MPa.

The gas pressure in coal not only characterizes the gas content in coal but also provides the required energy for desorption of the adsorbed gas molecules in coal. The higher the gas pressure, the greater the gas desorption energy in coal. Therefore, the gas desorption performance of coal was more profound. Studies have shown that as the gas adsorption pressure is increased, the initial velocity of coal gas desorption is significantly increased [32]. The corresponding cumulative gas desorption amount is greater for the same amount of time, and a higher gas pressure promotes the gas desorption of coal. With the gradual increase in the gas pressure, the cumulative gas desorption of coal also increases in stages [33–36]. It is thus possible to derive a significant increase in gas desorption by increasing the gas pressure. At the same time, the variation curve of the cumulative gas desorption and pressure under different temperature conditions obtained during the experiment was consistent with the trend of the curve obtained in Figure 6. Under the same conditions, the gas desorption amount of the coal sample gradually increased with increasing pressure, and the rate of increase gradually slowed down.

**4.4. Effect of the Moisture Content on the Desorption Characteristics of Coal.** To study the influence of the coal sample moisture content on the gas desorption characteristics of coal, the influence of the other four factors on the desorption characteristics of coal was excluded. First, the coal moisture content was selected as variable D, and the other four factors were defined as constant values. Second, the set of values was substituted into the equation, and the multivariate quadratic regression analysis equation was calculated and transformed. After that, the gas desorption amount per unit mass in 30 min,  $Q$ , was obtained as a function of the moisture,  $x_4$ . The intermediate-level values of the experimental design for the remaining four factors were as follows:

$$\begin{aligned} x_1 &= 0.75, \\ x_2 &= 0, \\ x_3 &= 3, \\ x_5 &= 140. \end{aligned} \quad (11)$$

The values of the above four factors were substituted into the multivariate quadratic regression analysis equation, and the relationship of  $Q$  with respect to the moisture content,  $x_4$ , was obtained, as shown in formula (12). The graph of the



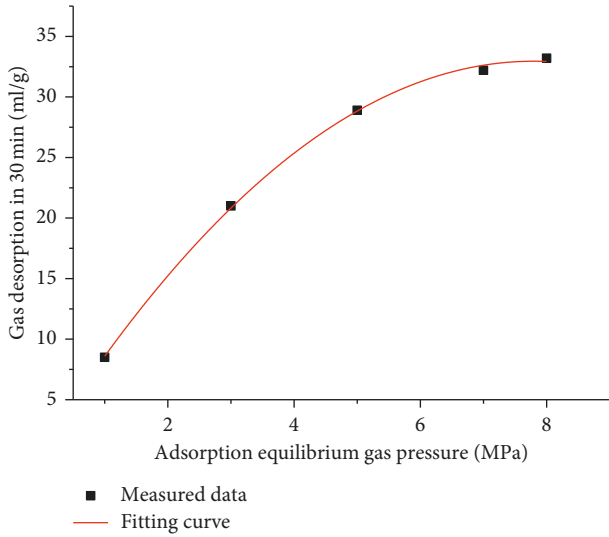


FIGURE 6: Curve of the gas desorption amount per unit mass in 30 min versus the pressure.

desorbed amount of gas per unit mass in 30 min as a function of the moisture content is shown in Figure 7:

$$Q = 24.27943 + 0.00095x_4^2 - 0.54658x_4. \quad (12)$$

According to Figure 7, with the gradual increase in the moisture of the experimental coal sample, the gas desorption amount per unit mass in 30 min was gradually reduced after coal sample equilibrium, and the moisture content reduced the gas desorption performance of the coal sample.

Coal is a naturally occurring porous medium that not only has a good adsorption effect on gas but also has a good adsorption effect on moisture. The adsorption of moisture by the coal sample not only reduced the adsorption area of gas on the surface of the coal sample, but the capillary phenomenon generated by the water in the coal sample also caused water molecules to enter the micropores and form capillary resistance. According to the previous analysis, it is known that the gas adsorption in coal mainly depends on the presence of a large number of pore volumes, such as micropores and mesopores, and a large specific surface area formed by the pore volume. However, the intervention of moisture blocks the pores so that the adsorption and desorption channels of gas are blocked, while the capillary resistance hinders the desorption and adsorption activity of methane molecules; thus, the desorption capacity of coal for gas is greatly reduced. According to the experimental studies by Pan and Li, the increase in the moisture content in coal can effectively reduce the initial velocity of gas emission and inhibit gas desorption. Therefore, the increase in the moisture content can significantly reduce the gas desorption capacity of coal. It has been recognized by many scholars and has been applied to engineering practices. Many mines have used water injection to increase the moisture content of coal before mining to suppress the desorption of coal gas, thereby reducing the risk of gas outburst [37, 38].

Figure 7 shows that the increase in the moisture content is very effective in inhibiting coal gas desorption, which is consistent with the experimental conditions. However, the

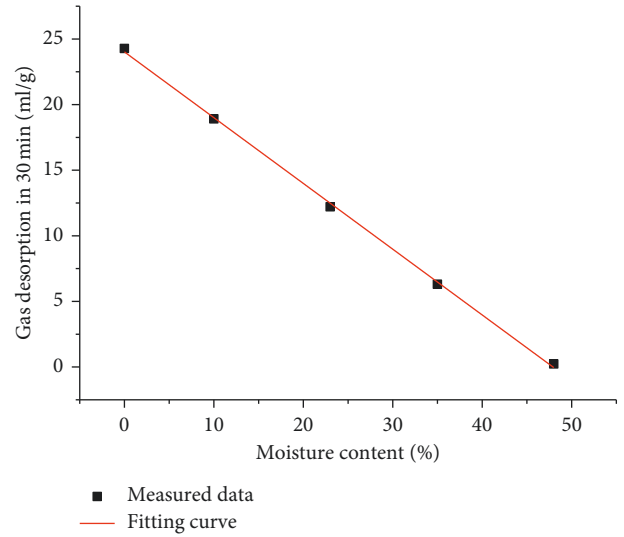


FIGURE 7: Curve of the gas desorption amount per unit mass in 30 min versus the moisture content.

influence of the moisture content on the gas desorption capacity of coal had a certain limit value similar to the particle size. When the coal sample moisture content was lower than the limit value, water had a significant inhibitory effect on the gas desorption performance of the coal sample. However, when the coal sample moisture content continued to increase beyond the limit value, the effect of the moisture content on the gas desorption performance of the coal sample gradually weakened and tended to be stable. At this point, the multivariate regression analysis equation did not reflect the limiting effect of the moisture content when the coal sample moisture content continued increasing. That is, when the coal sample moisture content was greater than the moisture content limit, the gas desorption capacity of the coal sample did not change significantly.

4.5. *Effect of the Molding Pressure on the Desorption Characteristics of Coal.* When studying the influence of the coal sample molding pressure on the gas desorption characteristics of coal, the molding pressure (variable  $E$ ) was selected, and the other four factors were defined as constant values. Second, the multivariate quadratic regression analysis equation was transformed, and the functional relationship of the gas desorption amount per unit mass in 30 min,  $Q$ , with respect to the molding pressure,  $x_5$ , was obtained. The intermediate-level values of the experimental design for the remaining four factors were as follows:

$$\begin{aligned} x_1 &= 0.75, \\ x_2 &= 0, \\ x_3 &= 3, \\ x_4 &= 6. \end{aligned} \quad (13)$$

The values of the above four factors were substituted into the multivariate quadratic regression analysis equation to obtain a function relationship of  $Q$  with respect to the

molding pressure  $x_5$ , as shown in formula (14). A graph of the gas desorption amount per unit mass in 30 min as a function of the molding pressure is shown in Figure 8:

$$Q = 8.31683 - 0.00067x_5^2 + 0.18457x_5. \quad (14)$$

According to Figure 8, the gas desorption amount per unit mass in 30 min as a function of the molding pressure gradually increased, but the gas desorption amount only changed within a small range. The gas desorption amount and adsorption performance of the coal sample increased and then decreased with increasing molding pressure, but the monotonic trend had no significant effect.

In this paper, the cold pressing method was used to make the briquettes to conduct the experiments. The moisture content, particle size, and molding pressure of the coal sample were different during the preparation of the briquettes. It has been found that an increase in the molding pressure when preparing briquettes to reduce the collapse pressure increases the strength of the coal samples, increases the bond in the coal samples, and reduces the pore volume in the coal briquettes. An excessive molding pressure can cause damage to the internal structure of the coal samples and even damage the coal briquettes. An appropriate amount of water can increase the internal bonding of the briquettes, but excessive moisture will produce a thicker water film and produce a slip effect on the briquette strength [39–42].

Although the increase in the molding pressure enhanced the contact between the coal particles to become tighter, the number of pores in the coal sample was relatively reduced. However, whether the molding pressure could significantly affect the micropore volume and specific surface area of the coal sample still requires further experimental research. Therefore, the effect of the variation in the coal sample molding pressure obtained by multivariate regression analysis on the gas desorption of coal requires further in-depth experimental research for verification purposes.

## 5. Conclusions

In this paper, the high-low temperature test equipment developed through independent design was used to perform the experimental research on the gas adsorption/desorption mechanism of coal under multifactor conditions including analysis and processing of test data. The factors affecting the gas adsorption/desorption of coal were studied by various settings of the level of change. The L25 ( $5^6$ ) orthogonal table was used to design the coal gas desorption and adsorption experiments by controlling the coal particle size, temperature, pressure, moisture content, and molding pressure. The orthogonal experimental sensitivity analysis and regression analysis were carried out on data of the gas desorption amount per unit mass in 30 min of 25 groups of experiments, and the following conclusions were obtained:

- (1) The sensitivity of the five factors with regard to the gas desorption amount per unit mass in 30 min was determined and exhibited the following order: C

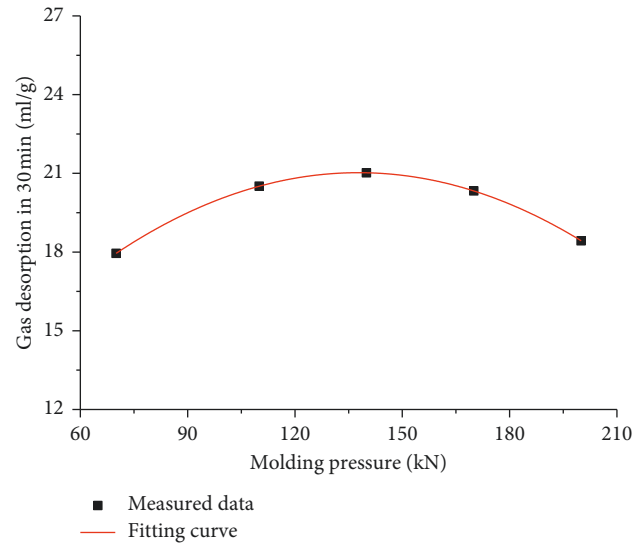


FIGURE 8: Curve of the gas desorption amount per unit mass in 30 min versus the molding pressure.

(pressure) > B (temperature) > A (particle size) > D (moisture content) > E (molding pressure).

- (2) Regression analysis of the experimental data showed that multivariate one-time regression analysis and multivariate quadratic regression analysis had high correlation coefficients. The regression analysis was effective and reasonable, and the correlation coefficient of the multivariate quadratic regression equation was higher than that of the multivariate one-time regression equation. In this paper, the multivariate quadratic regression analysis equation obtained in the regression analysis was used to analyze the experimental data.
- (3) The results on the influence of a single factor on the gas desorption capacity of a coal sample indicated that the coal gas desorption formula as a function of the coal sample particle size, temperature, pressure, or moisture content could well represent the trend of the gas desorption capacity of a coal sample with respect to various factors. The smaller the coal sample size was, the higher the ambient temperature was, the higher the gas pressure was, the smaller the coal sample moisture content was, and the greater the gas desorption amount per unit mass in 30 min after coal sample equilibrium was.

The orthogonal test results have important theoretical significance for guiding gas adsorption and desorption testing of coals. For coal and gas outburst prediction, the coal seam gas flow mechanism, coal gas content prediction, and calculation of the mining coal gas emission have important practical significance for gas explosion accident prevention.

## Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

## Acknowledgments

This work was financially supported by the National Science and Technology Major Project of China (Grant nos. 2016ZX05043005 and 2016ZX05045004), the State Key Research Development Program of China (Grant nos. 2016YFC0801404 and 2016YFC0801402), and the National Natural Science Foundation of China (51674050), which are gratefully acknowledged.

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